An automated static perimeter/adaptometer using light emitting diodes

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SUMMARY An automated static perimeter/adaptometer is described which measures thresholds with lights of 2 wavelengths. The instrument uses light-emitting diodes to produce the stimuli and is controlled by a small computer, making it very suitable for clinical testing of large numbers of patients. The use of 2 LEDs with different peak emission wavelengths (530 and 660 nm) permits an assessment of the relative state of rod and cone mechanisms in a particular region of the retina either during dark adaptation or when the eye is fully dark adapted.

A knowledge of the state of rod function relative to cone function in a particular part of the visual field is valuable in the diagnosis and management of retinal disorders and essential in any research on the nature of a particular disorder. Static perimetry on the dark adapted eye can provide much of the information required, and a number of instruments, notably the Tübinger perimeter,¹ have been designed to meet this need. However, static perimetry is not routinely used as a clinical technique on large numbers of patients because of the practical problems it presents: measurements take a long time to execute; the procedures are involved and require the full attention of a trained operator; most static perimeters are elaborate and expensive; analysis of results is complex and may need extra time and effort after the actual measurement. In this paper we describe a static perimeter/adaptometer which we have built from low-cost components; its automation proved straightforward because light-emitting diodes (LEDs) were used as sources for the stimuli. Computer control eases the burden on the operator and permits standardisation of procedure, especially in the pacing of a series of measurements and in the criteria used for establishing patient thresholds. Further, results can be analysed immediately after measurements have been completed. These improvements have enabled us to undertake a large-scale study of static fields in over 200 patients suffering from retinitis pigmentosa which will be described in detail in subsequent papers.

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Static perimeters and adaptometers often use a white light stimulus, but in the examination of an area of the visual field where thresholds are elevated it may be important to establish whether it is primarily rod function which is affected or whether there is a loss in both rod and cone systems. Measurements with white light cannot provide this information. To identify which mechanism determines the results, the best approach is to vary the spectral composition of the threshold stimulus. Spectral sensitivity plots can be derived from such measurements² and compared with the scotopic function if the rod pigment is presumed responsible for light absorption, or the photopic one if the cone pigments are at work, or a composite curve if rod and cone sensitivities are nearly equal. However, this approach requires the collection of a very large amount of data from each patient. A more practical method is to vary the stimulus between only 2 colours: Massof and Finkelstein^{3,4} have shown that satisfactory tagging of threshold data can be achieved when blue-green and deep red stimuli are used. In this paper we describe how we have adapted the 2-colour idea for our perimeter/adaptometer and demonstrate how our analysis of the results can distinguish between a selective disturbance of rod vision and a nonselective disturbance involving both rods and cones.

Materials and methods

PERIMETER CONSTRUCTION

A modified Lister perimeter⁵ forms the basis of the instrument we have built. The novel feature is that

the targets of this perimeter have been replaced with light emitting diodes (LEDs) used in such a way as to give a working range of 5 log units of light intensity change.

Fig. 1 is a diagram showing the main features of the perimeter. A single red LED has been placed at the centre of the arc to act as a fixation point for the detection of eccentric stimuli by the observer. The test stimuli are mounted on the target carriage. The recording equipment normally found at the back has been replaced by two reduction gear systems driven by stepping motors. The first drives the target carriage along the arm to a given eccentricity. The second rotates the arm so that the target is in the appropriate meridian. The observer's head is placed on a chin rest which can be adjusted so that the pupil of the eye being tested is at the centre of the arc described by the arm and the LEDs point at the pupil.

The test stimuli are formed from 2 adjacent LEDs, namely, Stanley ESBG5501 (green) and ESBR5501 (red) fitted into a small metal can. Each LED subtends an angle of 0.9° at the observer's eye. An Ilford 604 filter covers the green LED and 2 Ilford 608 filters the red one. Fig. 2 shows the spectral output of the LEDs unfiltered (dotted lines) and filtered (solid lines). It can be seen that the dominant wavelength of the green light is about 530 nm and that of the red light about 660 nm.

LUMINANCE CONTROL

The continuous current required to operate an LED at maximum luminance is about 20 to 60 mA at a

Fig 1 Modification of the Lister perimeter. The observer's right eye is shown being tested and the target carriage is at an eccentricity of 26° on the 0° (horizontal, temporal) meridian. The target can contains a red and a green LED (not shown).

Fig 2 Relative light output from Stanley ESBG5501 and ESBR5501 LEDs. Dotted lines: LEDs unfiltered. Solid lines: ESBG output passed through Ilford 604 filter, ESBR output passed through 2 Ilford 608 filters.

forward voltage of 1.6 to 2 V. The light intensity is a nonlinear function of current,⁶ approximating to a power law with an exponent of 1.3 to 1.5. While this nonlinearity may be unimportant in some applications, and can be compensated for over an intensity range of perhaps 1 to 2 log units, it is not really practical to control intensity over the wide range required for a perimeter simply by using variable-amplitude current drive. A better technique is to operate the LED in a pulsed mode and vary the pulse repetition rate. Since the pulse response of an LED is fast, with typical rise and fall times of 100 ns, pulse widths of less than 1 μ s and repetition frequencies of over 1 MHz are possible. At repetition rates above the critical flicker fusion frequency the eye does not perceive individual pulses but integrates them to give a time average. With a fixed pulse width the light intensity is a linear function of pulse repetition rate. We have therefore used repetition rate for coarse intensity control and current drive for fine steps.

Fig. 3 shows a block diagram of the system for controlling the output of the LEDs. Each LED is driven by its own current source (A) which can be programmed to produce 2 to 20 mA in preset steps of 0.1 log units. This provides fine intensity control over 0.9 log units. For most of the time transistor (Q) is on, shunting current away from the LED and turning it off. During the test presentation 1 μ s-wide pulses from the monostable (B) turn off transistor (Q) and turn on the LED. The pulse repetition rate is derived from clock 1 (C) which runs at 350 kHz. A decade divider chain (D) produces pulses at rates from 350 kHz to 35 Hz and pulses at one of these frequencies pass through the data selector (E) to trigger the monostable (B). This provides a further 4 log units of

Fig 3 Block diagram of components used to drive LEDs. For explanation see text.

intensity control in 1 log unit steps, giving a total range of 4.9 log units.

Dividing the intensity control into coarse and fine sections has the useful side effect that only 2 binary-coded decimal (BCD) digits are required to program intensity directly in log units. The perimeter can be placed under manual or computer control by data selector (F). Manual control is achieved by using clock 2 (G) to increment or decrement a BCD up/down counter (H) with a range of 0 to 49. A direct readout of the intensity setting in log units is provided by a 2 digit display (J). The timing of the test presentation is set at 200 ms on, 800 ms off by clock 3 (K).

Since each LED in the array is driven by its own current source, a red or green stimulus can be selected simply by removing the drive pulses from the unwanted section. This gating action is provided by the tri-state buffers (L) which also interface the CMOS control circuitry to the current sources.

The maximum luminance of the filtered green LED, corresponding to a reading of 4.9 on the display (J), is $0.9 \log \text{cd m}^{-2}$ and that of the filtered red one is $2.2 \log \text{cd m}^{-2}$. This results in normal observers giving mean log threshold readings of 1.2 and 1.4 on display (J) for the green and red stimuli, respectively, when tested parafoveally. Thus the stimuli can always be reduced below the threshold luminance of even the most sensitive observer tested in his/her most sensitive region. Further, the differences between the normal readings and the maximum available reading (4.9) are

sufficiently large for sensible quantification of threshold elevations in patients with retinal disorders.

AUTOMATION

The perimeter has been linked to a minicomputer (Plessey Micro 1) housed outside the darkened area in which the perimeter is placed. Before measurements are made the computer calibrates the rotary and eccentric movements of the stimulus by finding the number of pulses required by the stepping motors to move the perimeter arm and target carriage between the permitted extremes. The operator enters basic patient details, including an identifying number used to name a file that will contain the results of this test. Clinical notes may be entered and stored with the test results. The operator then calls for an 'instruction' file which contains all the information needed for the computer to test the patient in a defined manner—that is, the meridians to be investigated in appropriate order and the eccentricities and colours for which thresholds are to be measured.

When the patient is ready to begin the test, he/she presses a start button. On this signal the computer sets the intensity of the test stimulus to the lowest value possible and then increases it at a constant rate. As soon as the stimulus is visible, the patient presses a response key. The intensity value is stored, and the intensity is then decreased by an amount which varies randomly between 0.7 and 1.3 log units. This procedure is repeated until the standard error of the last 4

Fig. 4 Dark adaptation curves obtained from a normal observer (1 in Table 2) detecting the green and red stimuli at an eccentricity of 25° on the nasal, horizontal meridian of his right eye (180°). Open circles: red (660 nm) stimulus; closed circles: green (530 nm) stimulus. Ordinate: log relative threshold energy. All values are referred to the energy of the green stimulus when display (J)—see Fig. 3—shows a zero reading. The green stimulus then has a luminance of $-4 \log \text{cd m}^{-2}$. For full explanation see text.

responses is less than or equal to 0.1 log unit. Such a procedure is adopted to achieve a consistent set of data from which to estimate log threshold. As a precaution previous thresholds and individual response values are displayed graphically on a visual display unit for the operator, who if necessary can halt measurements to reinstruct the patient, slow down the rate of intensity change, or alter the statistical criterion used by the computer to define the patient's threshold. Once a series of readings are complete, the computer indicates this to the patient by a tone, and if the patient is ready to continue to the next set of measurements he presses the start button again. Measurements are organised so that the stimulus moves to successively greater eccentricities along a meridian. When a meridian is complete, the operator has the choice of continuing to another meridian, repeating the same meridian, or quitting the test. A patient is usually tested at between 30 and 40 locations in the visual field for the 2 stimuli (see Figs. 9 and 10). The procedure lasts about 25 minutes.

The results of all tests are stored immediately on the computer disc. A variety of programs are available for analysing the data, including averaging results from a number of observers so that groups can be compared. The most commonly used method of analysis is to obtain plots of the patient's threshold elevation compared with normal values as a function of eccentricity along individual meridians.

PROCEDURE WITH PATIENTS

Before the test the patients are shown the apparatus and given the opportunity to practise using the start and response keys. They are told that after pressing the start key they must look continuously at the steady red light and press the response key as soon as they become aware of a pulsing light, however faint, somewhere 'in the corner of the eye'. The patients are always informed of the particular meridian selected for testing. In the measurement of central thresholds, when the pulsing target obscures the fixation light, the patients are instructed to look directly for the pulsing light on its first appearance and to keep their gaze fixed once the target has been located. The operator usually remains with a patient until he is satisfied that the patient understands the nature of the test. If the patient seems slow to respond to the appearance of the test light, the operator slows down the rate at which the test light intensity is ramped up. Patients are given frequent reminders of the importance of keeping their gaze steady on the fixation light. Rest periods of several minutes are arranged for patients during the change-over from the investigation of one meridian to another.

The patients' pupils are always dilated for the test, usually with a mixture of phenylephrine and cyclopentolate. A minimum period of 20 minutes of dark adaptation is allowed before the first measurement. No correction is attempted for any defects in visual acuity.

Fig. 5 Photopic (solid line) and scotopic (dashed line) spectral threshold functions describing the data obtained at 3 instants (t_1 , t_2 , and t_3) of the dark adaptation experiment of Fig. 4. Ordinate as for Fig. 4. Letters A, C, and E indicate the position of the 660 nm dark adaptation curve at the 3 instants; letters B, D, and F indicate the position of the 530 nm curve; y indicates the log threshold minimum of the photopic function (at about 550 nm) which does not change between the instants; Y_1 , Y_2 , and Y_3 represent the successive minima of the scotopic function (at about 500 nm) as rod dark adaptation proceeds.

THEORY

Fig. 4 shows 2 dark adaptation curves obtained from a normal subject after a flash bleach covering the 0.9° test area which was centred at 25° on the horizontal nasal meridian of the right eye. Measurements were begun after an initial cone dark adaptation phase. Open circles are measurements made with a red test light (660 nm), while closed ones are those with a green test light (530 nm). At time t_1 both test lights were detected by the cone mechanism to give log threshold values of A and B. By time t_2 the rod mechanism had recovered sufficiently to be involved in the detection of the green light and give a threshold value of D. The detection of the red light was still mediated by the cones, and the log threshold, C, was equal to A. By t_3 the rod mechanism had reached its maximum sensitivity. There is a slight drop in threshold for the red test light, and it is possible that the measurement, E, was mediated by the rod mechanism, which clearly was also responsible for the value, F, obtained with the green light.

The relationship of these threshold changes to the

photopic and scotopic spectral sensitivity functions is shown in Fig. 5, where the reciprocals of CIE photopic and scotopic spectral sensitivity coefficients⁷ have been transformed into logarithmic ratios, allowing a direct comparison with Fig. 4; the curves are thus inverted log sensitivity functions. The figure shows the functions for the 3 instants of dark adaptation, t_1 , t_2 , and t_3 , labelled in Fig. 4. From Fig. 5 it can be seen that the difference between log threshold values A and B is characteristic of the photopic spectral threshold function, while the difference between E and F is characteristic of the scotopic one. A difference such as C–D (at t_2) which is greater than A–B but smaller than E–F indicates that the green light is being detected by the rods and the red one by the cones.

Fig. 5 shows that during dark adaptation the spectral threshold functions of rod and cone mechanisms are moving relative to each other. After cone adaptation the minimum log threshold of the cone function (at about 550 nm) equals y . At t_1 the rod function lies somewhere above the cone. Its exact position is unknown, but the curve has been placed to give a 530 nm reading, which corresponds to the extrapolated value of the rod dark adaptation curve at t_1 (Fig. 4). At t_2 the minimum log threshold of the rod function (at about 500 nm) equals Y_2 ; at t_3 , when the eye is dark adapted, it equals Y_3 . The difference between the log threshold minima for the two functions, $y - Y_3$, is dependent on the characteristics of the test target, also on the relative numbers of rods and cones in the region being tested, on their relative efficiency in absorbing the incident light, and on the temporal and spatial characteristics of the neural networks controlled by each type of receptor. The difference will determine whether the value E–F is equal to the value expected from a scotopic threshold function as shown in Fig. 5 or whether it is smaller. The latter condition results either from an overlap between the scotopic and photopic functions or, in the extreme case, the failure of the scotopic function to move below the photopic one.

Consider now what may happen in the dark adapted eye if there is a disturbance of rod and/or cone vision in the region due to disease. If both receptor mechanisms are affected and the cone spectral threshold function moves up to the same or to a greater extent than the rod one, then the latter will continue to describe measurements at 530 and 660 nm. Hence the log threshold elevations relative to normal, $(E' - E)$ and $(F' - F)$, will be equal as illustrated in Fig. 6. However, if the rod function moves up while the cone function remains undisturbed, or if both functions move up but the rod one to a greater extent, then the resulting situation becomes analogous to that observed in a normal

Fig. 6 Normal scotopic and photopic spectral threshold functions in the dark adapted eye (left panel) and both functions elevated to the same extent by disease (right panel). Ordinate as for Fig. 4. For explanation see text.

observer at various instants before dark adaptation is complete. From Fig. 4 it can be seen that (D-F) is greater than (C-E) or that (B-F) is greater than (A-E): there is a greater log threshold elevation for the green light than for the red one.

In our presentation of perimetry results from patients tested at a series of locations we show in 2 separate panels their log threshold elevations for the 2 stimuli relative to normal values. The normal values are means obtained from 10 to 30 individuals. We also display in a third panel the difference between the log threshold elevations (green minus red) which we have called the green-red index. When the index is zero, it can be seen from Fig. 6 that the disorder is affecting the cones to the same or greater extent than the rods. Consider now the other extreme possibility, namely, rod function is so much more affected that the patient's thresholds for both green and red light are mediated by cone vision. Under these conditions the index assumes a maximum positive value. Here it may be helpful to compare the patient with the normal observer at t_1 during dark adaptation and to refer to Fig. 4. The log threshold elevation for green is (B-F) and for red is (A-E). The index is therefore (B-F)-(A-E) or (E-F)-(A-B). Thus the maximum value of the index represents the difference

seen in the rod spectral log threshold function for the 2 wavelengths less the difference seen in the cone function. It is a measure of the Purkinje shift in moving from one spectral threshold function to the other and is dependent only on the characteristics of the 2 functions. The last statement, however, does require qualification in one respect. In some regions of the normal retina the state of affairs shown for t_2 in Fig. 4 may represent the final state of dark adaptation, that is, the 2 spectral functions do not separate sufficiently for the scotopic function to describe the final measurement with the red test light. In these circumstances the maximum value of the index will be reduced by an amount which can be calculated if the separation of the functions is known.

To summarise, a disturbance in rod function in a particular region can be identified by a log threshold elevation for the green test light. Figs. 4 and 5 show that elevations up to about 2 log units are measures of the loss of rod function. The interpretation of greater elevations requires knowledge of what is happening to the cones. If there is little deviation from normal in the red measurement, the cones in the region are

Fig. 7 Data from an RP patient examined on the LED perimeter (filled circles, solid line) compared with data from the same patient tested on a Tübinger perimeter (open circles, dashed line). Dotted line represents the average performance of a group of normal observers examined on the LED perimeter under the same conditions as the patient. Dominant wavelength for red stimulus: 626 nm for the LED perimeter; 600 nm for the Tübinger. For full description see text. A zero value on the log threshold axis corresponds to a luminance of $-4.9 \log \text{cd m}^{-2}$ for the red LED.

being spared by the disease. If, however, there is an elevation of the log threshold reading for the red light, the index needs to be examined to determine whether, on the one hand, the disturbance is affecting cone vision to at least the same or to a greater extent than rod vision or, on the other, it is rod vision which is being disturbed to a greater extent. In the former case the index will be close to zero; in the latter it will have a significant positive value. Provided the index is less than its maximum possible value for the given location, the elevation in the green measures rod loss. However, when the index maximum is reached, the detection of both red and green stimuli is mediated by the cones, and only a lower limit can be set on the extent of rod loss.

Results

RELIABILITY OF THE LED PERIMETER/ADAPTOMETER

The Tübinger perimeter has been extensively used to map complex rod abnormalities in retinitis pigmentosa (RP).^{3,4} Fig. 7 shows thresholds for the right dark adapted eye of a sufferer from the autosomal dominant form of RP. The open symbols joined by the dotted line represent measurements made with a Tübinger perimeter. The 15° meridian of the right eye was chosen; the target subtended 1.1° at the patient's eye; the colour filter resulted in the stimulus light having a dominant wavelength of 600 nm; the duration of the stimulus was 200 ms; thresholds were determined by the operator using an ascending method of limits with single flash presentations. Seven weeks later the patient was tested with our automated LED perimeter. The same meridian was examined; the target was smaller, namely, 0.9°; the dominant wavelength of the light output from the LED was 626 nm (in this experiment the prototype perimeter was used—see 'Discussion'—and the LED was a Hewlett Packard 5082-4658 and not the Stanley ESB5501); the stimulus lasted 200 ms and was repeated every second; measurements were collected automatically, as described. The results are shown as the filled symbols joined by the solid line. The Tübinger measurements have been scaled to equal the LED ones at a 10° eccentricity. It can be seen that both types of measurement gave rise to similar shaped profiles of visual function along this meridian.

Fig. 8 shows the degree of reproducibility that can be expected in data obtained from an RP patient tested under the same conditions over 2 sessions. The open symbols represent data obtained from the first session, while the filled symbols refer to data obtained 2 months later. Circles represent measurements made at the beginning of the session; squares are readings recorded after 2 other meridians were investigated.

Fig. 8 Threshold measurements on an RP patient collected during 2 sessions 2 months apart and at different times during each session. Circles: measurements at the beginning of each session; squares: measurements made at the end of each session; open symbols: measurements made at the first session; closed symbols: measurements made 2 months later. Green stimulus; horizontal nasal meridian of the right eye. A zero log threshold reading corresponds to a luminance of $-4 \log \text{cd m}^{-2}$.

To check the validity of using the green-red index to label rod and cone function we carried out a series of dark adaptation experiments of the type illustrated in Fig. 4 on a number of normal observers for a variety of locations in the visual field. The results are summarised in Table 1. Column 1 identifies the observers. Column 2 identifies the locations in the visual field of

Table 1 Separation of photopic and scotopic spectral curves and green-red indices for various retinal locations

1	2	3	4	5
Observer	Eccentricity, $y-Y_3$ degrees	Expected index maximum	Expected index maximum	Observed index maximum
1	5N	2.0	2.0	1.6
1	25N	2.0	2.0	1.8
2	5N	1.9	1.9	1.6
2	25N	2.3	2.3	1.9
3	5N	2.2	2.2	1.8
3	25N	2.1	2.1	2.3
4	10T	2.5	2.3	2.0
4	20T	3.0	2.3	2.1
4	40T	2.8	2.3	2.4
4	80T	2.7	2.3	2.0

N = nasal. T = temporal.

Fig. 9 Analysis of RP data. Log threshold elevation relative to normal for green stimulus (left panel) and for red stimulus (middle panel), and the green-red index (right panel) plotted as a function of eccentricity on 4 meridians of the right eye (0° , 315° , 225° , and 160°). Patient: AD RP type 1.

the right eye. All locations are on the horizontal meridian and are defined in degrees of eccentricity; N refers to nasal, T to temporal. The separation in column 3 refers to the distance between the minima of the rod and cone spectral threshold functions; $y-Y_3$, as illustrated in Fig. 5. The values are derived from measurements with the green stimulus and from published data on the 2 functions. Column 4 gives the expected index maxima derived from column 3. At 660 nm the threshold for the photopic function was elevated by 1.2 log units relative to its minimum; the corresponding value for the scotopic function was 3.5 log units.⁷ Therefore, in theory, for the red light measurements to be described by the scotopic function the separation between the minima of the 2 functions must equal or exceed 2.3 log units for the given region of retina being considered. If that is the case, the maximum theoretical value of the index can be calculated from the 2 functions. It is given by $(E-F)-(A-B)$ (see Fig. 4). This turns out to be 2.3 log units. If, however, the separation between the 2 functions falls short of the 2.3 value by an amount x log units, then x must be subtracted from 2.3 to give the expected index maximum. An empirical index maximum can also be calculated from each observer's data for a given location by subtracting the green from the red log threshold values during the cone plateau of dark adaptation to make difference (1),

doing a similar subtraction for the period at the end of dark adaptation to make difference (2), and finally subtracting difference (2) from difference (1). Such double differences are shown in column 5. In general, the empirical values were lower than the ones calculated from the 2 functions. Detailed examination of the data shows that, whereas the CIE based scotopic function gives a very good description of the measurements made on the dark adapted eye, the photopic function consistently underestimates the log threshold value for the red test light by about 0.2 log unit. In the analysis of data we have accordingly decreased the expected index maximum by 0.2 log unit.

EXAMPLES OF THE CLINICAL APPLICATIONS OF THE LED PERIMETER/ADAPTOMETER

Fig. 9 illustrates the way we usually analyse our patient data. The example shown is for a 12-year-old boy suffering from the autosomal dominant form of RP. Table 2 outlines how the plots are constructed from readings for the 0° meridian. Each of the mean normal values is subtracted from the patient value to give a log threshold elevation or green-red index. Asterisks in the table and upward arrows in the figure indicate that the patient was unable to see the stimulus at its maximum luminance. The 'green' and 'red' plots suggest that the patient had a ring scotoma

Table 2 RP patient data for 0° meridian of the right eye compared with normal

Eccentricity	Patient green	Normal green	Elevation green	Patient red	Normal red	Elevation red	Patient green-red	Normal green-red
0	3.5	2.1	1.4	1.7	1.4	0.3	1.8	0.7
5	3.5	1.5	2.0	1.9	1.5	0.4	1.6	0.0
10	3.3	1.4	1.9	2.1	1.7	0.4	1.2	-0.3
20	3.5	1.7	1.8	1.9	2.0	-0.1	1.6	-0.3
25	3.7	1.5	2.2	2.0	2.0	0.0	1.7	-0.5
30	3.5	1.5	2.0	2.2	1.8	0.4	1.3	-0.3
35	3.7	1.6	2.1	*	2.0	*	*	-0.4
40	*	1.6	*	*	1.9	*	*	-0.3
45	*	1.8	*	*	2.0	*	*	-0.2
50	*	1.8	*	2.1	2.1	0.0	*	-0.3
55	*	2.0	*	*	2.3	*	*	-0.3
60	*	2.1	*	*	2.3	*	*	-0.2
65	3.8	2.2	1.6	*	2.4	*	*	-0.2
70	3.7	2.3	1.4	2.2	2.5	-0.3	1.5	-0.2

developing. Examination of the index shows that for almost all readings it is close to its maximum value, indicating that, even when the patient had some residual rod function, rod thresholds lie well above cone ones. At least in some regions cone function was near normal, since the 'red' readings were close to the zero line.

Fig. 10 shows a similar set of plots from another patient with autosomal dominant RP. Here it is clear that the pattern of disease is very different. There is evidence of a ring scotoma but in regions where the

log threshold elevation could be measured the index was close to zero, indicating a generalised disturbance of rod and cone function and not a selective rod loss. The comparison between Figs. 9 and 10 illustrates the importance of 2-colour static perimetry in differential diagnosis.

Fig. 11 demonstrates the importance of the 2-colour technique in the correct interpretation of adaptometric results.

These data are taken from a study of patients with liver disorders (Kemp, Ernst, Walt, Sherlock, Lyness,

Fig. 10 Analysis of RP data. See legend to Fig. 9. Patient: AD RP type 2.

Fig. 11 Dark adaptation data obtained from a patient suffering from a liver disorder. Details as in Fig. 4. Open symbols: red stimulus; closed symbols: green stimulus.

and Bird, unpublished) and can be compared with the normal data illustrated in Fig. 4, since they were obtained under very similar conditions. If the measurements had been conducted with just the green stimulus, the interpretation might easily have been made that part of the curve represented rod dark adaptation, albeit abnormal. However, the additional readings with the red light show that the whole of the dark adaptation displayed is due to the cones and that it is very significantly delayed relative to normal.

Discussion

The usefulness of measuring spectral sensitivity in cases of RP was first appreciated by Zeavin and Wald.⁸ Massof and Finkelstein^{3,4} demonstrated that, where large numbers of individuals and limited testing time were involved, a practical solution was to restrict measurements to 2 stimuli of different colours, one blue-green (500 nm) and the other deep red (650 nm). In more extensive spectral measurements on normal observers and RP patients, Massof *et al.*² confirmed the validity of this approach. We have therefore designed our automated static perimeter to have 2 spectrally distinct stimuli. Like Massof and Finkelstein^{3,4} we have found at least 2 distinct sub-types of autosomal dominant RP. In one—classified as type 1 by Massof and Finkelstein⁴—the disturbance in rod function occurs early, is diffuse, and may be so severe that thresholds in the dark adapted eye are mostly mediated by cones. The case of the 12-year-old boy illustrated by

Fig. 9 falls into this category. In a second subtype—type 2—there is a combined elevation in rod and cone thresholds. The patient of Fig. 10 is an example of this group. An extensive analysis of more than 50 patients with autosomal dominant RP will be dealt with in a subsequent paper (Lyness, Ernst, Quinlan, Clover, and Parker, in preparation).

While our main use for the perimeter/adaptometer has been in a study of retinitis pigmentosa, it may have important applications in other clinical fields. The interpretation of the dark adaptation curves shown in Fig. 11 as due to delayed cone recovery clearly rests on the 2-colour technique.

To maximise the effects of the transition from a scotopic to a photopic spectral sensitivity function the optimum choice for the 2 test stimuli is a pair of monochromatic lights with wavelengths of about 480 and 670 nm. Unfortunately, until recently, commercially available LEDs with a sufficiently high light output have produced their peak emission in the range 560 to 635 nm. In developing the perimeter we began with a prototype which used Hewlett-Packard LEDs, 5082–4958 (green, dominant wavelength after filtering 550 nm) and 5082–4658 (red, dominant wavelength 626 nm). The maximum value for the green-red index was about 1.2. We were able to increase this to 1.6 by exploiting the greater spatial summation properties of rod compared with cone vision. Instead of a single green LED as one of the test stimuli we arranged 6 to form a ring around the red LED. The light from the ring, when diffused, appeared as an annulus. With this arrangement the

readings for green and red log thresholds no longer belong to the same spectral log threshold function. Instead the former is part of an 'annulus' function which lies about 0.4 log unit below the 'spot' function of which the red reading is a part. Analysis of thresholds measured with spots and annuli at various eccentricities and also comparisons of patient performance on the Tübinger and LED perimeters suggested that no major problems would be encountered with the annulus/spot arrangement, and useful information from a number of patients was obtained with the technique. Nonetheless it does introduce an additional complication into the interpretation of the green-red index. Therefore as soon as the Stanley LEDs became available—in particular the ESR5501 with a light output at 660 nm—the stimuli were changed to 2 single LEDs. The change in wavelength of the red light from 626 to 660 nm increased the maximum index value from 1.2 to near 2.0 log units. The change in the green light from 550 to 530 nm has contributed a further 0.1 log unit. This performance now approaches that of a Tübinger perimeter. In future it may be possible to increase the maximum value of the index further through the use of a blue LED in place of the green one. Such LEDs are now commercially available.

To enable us to make comparisons of data obtained with our earlier perimeter and the one now in use we have expressed our results in terms of the extent to which a patient's performance at a given eccentricity deviates from normal performance for the same stimuli. This extent is quantified as a log threshold elevation. It has therefore been convenient to construct an index of scotopic/photopic function from the difference between log threshold elevations for green and red stimuli. Since for most regions of the visual field normal thresholds for both green and red stimuli are characteristic of the scotopic function, the green-red index is in general a measure of the patients' deviation from a scotopic threshold match for the 2 stimuli. A near zero value indicates that the patient is using his/her rods for threshold detection, whereas a near maximum value indicates that the patient is dependent on cone function. By contrast, Massof and Finkelstein^{3,4} use a different measure to identify rod or cone function, namely, the difference between the values given by a patient for the absolute threshold luminances of red and blue-green lights. Since the luminances are expressed in photopic units, the difference (approximately) expresses a patient's deviation from a photopic threshold match. In fact, for reasons discussed by Massof and Finkelstein⁴ a value of about -0.3 rather than zero is expected when the patient is using cone function for threshold detection and a value of 1.9 when he/she is using rod function. However, the range of the Massof and

Finkelstein measure (2.2 log units) corresponds approximately to the maximum value of the index, and the 2 measures can be compared.

We have not monitored eye position with the present instrument. While it would be possible to modify it to do so by the use of an infrared television camera or a commercially available eye movement monitor, the cost would be high, and such a change would undoubtedly introduce a new set of problems (reduction of light, restriction of view, etc.). In general, patients coming to assist in research are highly motivated, and the importance of good fixation can be impressed upon them. Moreover, most patients with RP have reasonable central vision and are able to achieve good fixation, as judged from observations on the Goldman perimeter. The results shown in Figs. 7 and 8 provide examples that in practice patients can achieve satisfactory fixation.

The great advantages of our instrument lie in the ease with which it can be used even by a relatively unskilled operator, the fact that it does not require the operator's full-time attention throughout the whole test, and the fact that the results are graphically displayed even during the test, while a full analysis is available immediately on completion. This has meant that it has become practical for us to include 2-colour static perimetry as a routine part of a clinical investigation of a large number of patients rather than as an exceptional test to be carried out laboriously only on a selected few patients.

Our thanks are due to Miss C. Wheeler for making the measurements on the Tübinger perimeter and to Mr R. J. H. Smith for allowing us to use his instrument, to the workshop of the Institute of Ophthalmology for help in the construction and maintenance of the LED perimeter, especially to Mr G. Mould, and to Mr G. Joseph, Mr R. Carter, and Mrs K. Shah for technical assistance. We gratefully acknowledge financial support from the UK Medical Research Council, the British Retinitis Pigmentosa Society, the American Retinitis Pigmentosa Foundation, and the Golden Nugget Fund. Throughout the project we received advice and encouragement from Professor Alan Bird and Mr Barrie Jay. We would especially like to thank all those persons who volunteered to act as normal observers in the calibration of the instrument.

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